



Influence of environmental and operational variables in commercial fishery landings: The case of pair trawlers in southeastern Brazil

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HIGHLIGHTS

- Patterns of pair trawl fisheries landings in Brazil are investigated.
- Fisheries yields are higher in summer and spring months.
- Landings of the main categories of fish are mostly related to sea temperature and chlorophyll concentration.

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ABSTRACT

Faced with the overexploitation reality of many of the world fish stocks and climate change, understanding the relationships between catches, fishing strategies and environmental conditions becomes crucial. In this context, this study aimed to describe the correlations between operational and environmental variables in landings of the main fish categories by pair trawl fisheries off the coast of southeastern Brazil. Catch composition varied greatly between 2003 and 2011. This change was mainly related to the shift of the fishing area to greater latitudes and variations in sea surface temperature and chlorophyll concentrations. The physical characteristics of the vessels and fishing gear did not change during the study period. Environmental variables most likely influence stock catchability, primarily by changing their distribution pattern, indicating a shift in ocean characteristics that will influence this dynamic. This draws attention to the need to maintain monitoring programs to apply adequate management measures for the protection of fish populations, consequently ensuring fishing activities in the area.

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1. Introduction

The collection and analysis of fisheries data support decision-making in different spheres of fisheries sector and fisheries management (Perry et al., 2010). Nevertheless, the variations in catch abundance is not only related to stock abundance. Environmental and operational drivers have been pointed out by several authors as components that significantly affect the final behavior of fisheries and their catches (Link et al., 2010; Graaf et al., 2011; van Putten et al., 2012; Stephenson et al., 2018).

In general, environmental conditions influence the distribution and abundance of marine organisms, controlling these factors either indirectly, through competition, predation and resources availability, or directly, affecting their physiology (Jennings et al.,

2001). This influence can be reflected in the commercial fishing catch rates of different species. Variables such as water temperature, chlorophyll concentrations, wind speed and moon phases have been demonstrated as influencing fisheries catch rates for different organisms (Bigelow et al., 1999; Dawe et al., 2007; Hobday and Tegner, 2002). Regarding demersal fish, there is evidence that warmer temperatures increase productivity, as reported for Atlantic cod (*Gadus morhua*) in Norway (Godø, 2003) and Atlantic croaker (*Micropogonias undulatus*) on the east coast of the United States (Hare and Able, 2007). In addition, environmental variables have been shown to impact the landings of other demersal organisms. Common octopus (*Octopus vulgaris*), for example, presents increased fishery production in lower temperatures (Chédia et al., 2010), while the opposite has been registered for deep-water rose shrimp (*Parapenaeus longirostris*) (Benchoucha et al., 2008). Changes in the environment can also trigger changes in species behavior, influencing stock catchability. Maynou and Sardà (2001), for example, attributed the increase in light intensity that reaches the bottom to the increased Norway lobster (*Nephrops norvegicus*) vulnerability to trawling.

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However, cases in which operational variables influence catch rates more than the environment have also been reported. For example, Damalas et al. (2007) found that thicker and highly resistant longline hooks, placed deeper and with illuminated fish attractants led to significantly higher swordfish (*Xiphias xiphias*) catches. Another example is the study carried out by Rose and Nunnallee (1998), in which a narrower trawl net mouth opening resulted in a higher catch per swept area for sole (*Hippoglossoides elassodon*) and *Atheresthes stomias*) and Alaska pollock (*Gadus chalcogramma*). Therefore, to truly detect the role environmental variables play on fish stocks dynamics, it is crucial to analyze fishing characteristics and quantify how much they are influencing fish yields.

In this context, pair trawling is an important industrial fishery in Brazil, contributing with approximately 53.8% of demersal fish landings in the southern region between 1975 and 1994. Other relevant demersal fisheries in the area are also carried out, such as otter trawling and the use of bottom gillnets (Haimovici, 1998).

Pair trawling is characterized by two vessels that haul a single net through the sea bed, with a mesh size equal to or larger than 90 mm in the tunnel and bag, measured between opposite corners of the stretched mesh, according to Brazilian legislation. The net opening can reach 55 m horizontally and 6 m vertically (Castro and Tutui, 2009). This fishery presents high multi-specific catches that mostly land Sciaenidae fish, such as whitemouth croaker (*Micropogonias furnieri*), Jamaica weakfish (*Cynoscion jamaicensis*) and king croaker (*Menticirrhus* spp.), as well as several weakfishes (*Cynoscion* spp. and *Macrodon atricauda*), in addition to the grey triggerfish (*Balistes capriscus*), several species of catfish (Ariidae) and flounder (Paralichthyidae) (Valentini et al., 1991).

Vessels belonging to this fleet operate relatively steadily in relation to fishing days, number of hauls per day, duration of each haul and fishing gear characteristics. However, when the time series (1975–1998) of the pair trawling fishery was analyzed, changes over the years in boat engine power (HP), size and tonnage were observed, which could also influence productivity and landing values (Castro and Tutui, 2009).

It is crucial to understand the factors that influence commercial fishing landings, in order to conduct inferences on controlling stock mechanisms. This also allows for further comprehension of complex fisheries dynamics, enabling the development of more appropriate and effective management tools. This is especially true in face of a region in which fisheries in general and their dynamics are poorly understood, with little available published literature, leading to large knowledge gaps in building management plans and basis for political decisions in the region. In addition, due to the reality of climate change, it is essential to understand how environmental variables are correlated with fish stocks, allowing forecasts not only related to alterations in fish biology and behavior, but also how this might affect fisheries social and economic aspects in a recent future.

Considering this context, the present study aimed at investigating pair trawl fisheries dynamics in southeastern Brazil, in order to identify composition, abundance and spatial distribution patterns of caught species related to temporal, environmental and operational drivers.

2. Materials and methods

The study area corresponds to the continental Southeastern Brazil shelf between 24°S and 28°S, approximately 60 m deep (Fig. 1). Fisheries data used in the study (number of hauls, depth and fishing area) and landings values for each fish category by trip between 2003 and 2011 were obtained from the São Paulo State Fisheries Institute Monitoring Program (PMAP) database. This program uses the census method through dockside interviews conducted at the main ports in the state of São Paulo, Brazil.

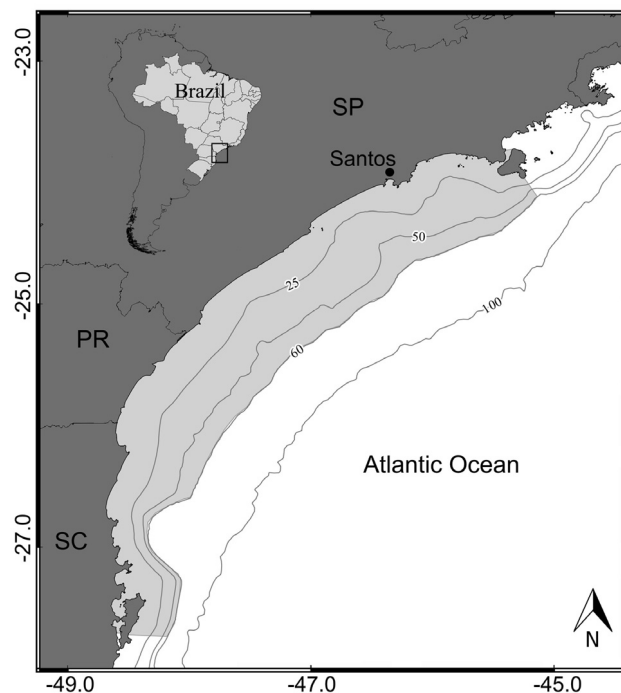


Fig. 1. Map of the study location with the area used to spatial analyses in light grey.

Data from 1379 trips of the pair trawl fleet carried out from 2003 to 2011 were used for the analysis, representing 91% of available trips. Non-analyzed trips exhibited incomplete data.

The variables used to describe trips were year, month, season (quarter), average depth (maximum depth + minimum depth of the trip ÷ 2) and latitude, as well as physical characteristics of the vessels, such as engine power (HP), gross tonnage (t) and length (m) of the smaller vessel of each pair trawler. Physical data were obtained from both PMAP and Fishing General Registry (RGP) of the Ministry of Fisheries and Aquaculture. Operational information was given during dockside interviews.

The following environmental variables were evaluated:

(1) Monthly means of sea surface temperature (SST, in °C), obtained from the Physical Oceanography Distributed Active Archive Center (PO.DAAC), at NASA (National Aeronautics and Space Administration); with a 9 km resolution, measured during the day and by the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor with AQUA satellite;

(2) Monthly means of chlorophyll concentrations (mg m^{-3}), obtained from the Ocean Color Web at the NASA database; with a 4 km resolution, and also through the MODIS sensor with AQUA satellite;

(3) Bimonthly Multivariate Enso Index (MEI) values obtained from the Earth System Research Laboratory from NOAA, representing a climate variability scale pattern. It is related to variations in ocean–atmosphere interactions in the lower latitudes of the Pacific Ocean, and it is important to be taken into account, since it influences global climate and interannual time scales. Positive values represent the warm phase of the El Niño, while negative values represent the cold phase, or La Niña (Wolter and Timlin, 2011);

(4) Monthly values of the Antarctic Oscillation Index (AAO), obtained from the Climate Prediction Center at NOAA. This index, also known as the Southern Hemisphere Annular Mode, is a climate variability scale pattern that refers to large-scale alternations of atmospheric mass between the surface pressure of the middle and

Table 1

List of fish categories used in the study with the common and scientific name.

Category	Species	Family
Catfish	–	Ariidae
Grey triggerfish	<i>Balistes caprisus</i> Gmelin, 1789	Balistidae
Leatherjacket	<i>Oligoplites</i> spp.	Carangidae
Lookdown	<i>Selene</i> spp.	Carangidae
Snook	<i>Centropomus</i> spp.	Centropomidae
Barred grunt	<i>Conodon nobilis</i> (Linnaeus, 1758)	Haemulidae
Squid	<i>Doryteuthis</i> spp.	Loliginidae
Flounder	–	Paralichthyidae
Atlantic bigeye	<i>Priacanthus arenatus</i> Cuvier, 1829	Priacanthidae
Guitarfish	<i>Rhinobatus</i> spp.	Rhinobatidae
Acoupa weakfish	<i>Cynoscion acoupa</i> (Lacepède, 1801)	Sciaenidae
Stripped weakfish	<i>Cynoscion guatucupa</i> (Cuvier, 1830)	Sciaenidae
Jamaica weakfish	<i>Cynoscion jamaicensis</i> (Vaillant & Bocourt, 1883)	Sciaenidae
Smooth weakfish	<i>Cynoscion leiarchus</i> (Cuvier, 1830)	Sciaenidae
Green weakfish	<i>Cynoscion virescens</i> (Cuvier, 1830)	Sciaenidae
Shorthead drum	<i>Larimus breviceps</i> Cuvier, 1830	Sciaenidae
Southern king weakfish	<i>Macrodon atricauda</i> (Günther, 1880)	Sciaenidae
Kingcroaker	<i>Menticirrhus</i> spp.	Sciaenidae
Whitemouth croaker	<i>Micropogonias furnieri</i> (Desmarest, 1823)	Sciaenidae
Barracuda	<i>Sphyraena</i> spp.	Sphyraenidae
American harvestfish	<i>Pepilus paru</i> (Linnaeus, 1758)	Stromateidae
Largehead hairtail	<i>Trichiurus lepturus</i> Linnaeus, 1758	Trichiuridae
Bluewing searobin	<i>Prionotus punctatus</i> (Bloch, 1793)	Triglidae

high latitudes (Gong and Wang, 1999). Annular modes, both from the southern and the northern hemisphere, describe atmosphere flow variations that are not explained seasonally.

For the data analysis, 23 out of 89 landed fish categories were selected. The term fish category was preferred, since landings are not necessarily reported at species level, and may also be indicated at higher taxonomic levels. The selection of these landing categories considered their participation both regarding amount, where these categories corresponded to 85.1% of total landed weight, and frequency of occurrence, where the minimum was of 10.4%, also corresponding to the most relevant categories for the fisheries' revenue (Table 1).

Landings per unit effort (LPUE) were determined per trip, and fish category as the amount in kilograms divided by the number of hauls. The LPUE matrix of the fish categories landings per trip was logarithmized $\log(x+1)$ and subjected to an agglomerative hierarchical clustering (Cluster), which grouped trips with similar landings composition. The Bray–Curtis method was used to calculate the similarity matrix, since it ignores double absences (Zuur et al., 2007). Ward's minimum variance method was used to build the cluster and group consistency was verified by the cophenetic correlation coefficient, which is the Pearson correlation coefficient (r) between the distance matrix and the cophenetic matrix. The significance of dissimilarity variations between the groups was determined by a non-parametric statistical analysis of similarities (ANOSIM) (Legendre and Legendre, 1998).

To assess the influence of operational variables on the landing composition, the groups were described according to the vessel characteristics, and the trips by their most common values, given by the interquartile range. In the case of categorical variables, levels whose frequencies, decreasingly ordered, summed at least 50% of the trips were indicated. Normality and homoscedasticity of the numerical variables were verified by the Shapiro–Wilk (Shapiro and Wilk, 1965) and Bartlett (Zar, 2010) tests, respectively. The significance of the variation of these factors by group was quantified by the Kruskal–Wallis test, followed by the Kruskal Multiple Comparisons test (Kruskal MC) (Siegel and Castellan, 1956).

The analysis of indicator species (Indicator Value Index – IndVal) was used to select the indicator fish categories of each group formed by the cluster (Dufrêne and Legendre, 1997). This index is determined by the product of specificity (A_{kj}) and fidelity (B_{kj}) for each species j for each cluster of landings k , as follows:

$$A_{kj} = \text{Nindividuals}_{kj} \div \text{Nindividuals}_{+k}$$

$$B_{kj} = \text{Nlandings}_{kj} \div \text{Nlandings}_{k+}$$

$$\text{INDVAL}_{kj} = 100 A_{kj} B_{kj}$$

in which Nindividuals_{kj} is the mean abundance of species j across the landings belonging to cluster k ; Nindividuals_{+k} is the sum of the mean abundances of species j within the various clusters; Nlandings_{kj} is the number of landings in cluster k in which species j is present and Nlandings_{k+} is the total number of landings in that cluster. The indicator value for each species is given by the largest value of INDVAL_{kj} found over all clusters k (Dufrêne and Legendre, 1997). Monthly temperature and chlorophyll- a data for the study area were cropped from MODIS-Aqua imagery for calculations regarding their minimum, mean and maximum values.

The LPUE and environmental variable time series were analyzed by applying autocorrelation functions in order to detect trends and seasonal variations. In addition, cross-correlation functions within environmental variables and between LPUE and environmental variables were applied to verify correlations during the study period, considering time lags of up to two years. These functions are based on the Pearson correlation coefficient (r), measuring the strength of the linear relationship between two variables (Zuur et al., 2007). For this analysis, only categories of fish that were significant indicator species of the groups formed by the cluster were selected. When the group exhibited more than one indicator category, only the most abundant were considered, totaling eleven categories.

The analyses were performed using the statistical software R, version 3.4.1 (R Core Team, 2017), including the vegan (Oksanen et al., 2013), labdsv (Roberts, 2016) and pgirmess (Giraudoux, 2017) packages.

3. Results

3.1. Landings composition and operational variables

The average number of hauls performed by pair trawlers per day was 4.2, with a minimum of 1 and a maximum of 8. Mean landings per haul were equivalent to 643.7 kg, ranging from 29.6 kg to 1855.8 kg.

The cluster analysis (Fig. 2) demonstrated a high variability of catch composition throughout the study period. The dendrogram's cophenetic correlation coefficient was 0.35. Seven groups

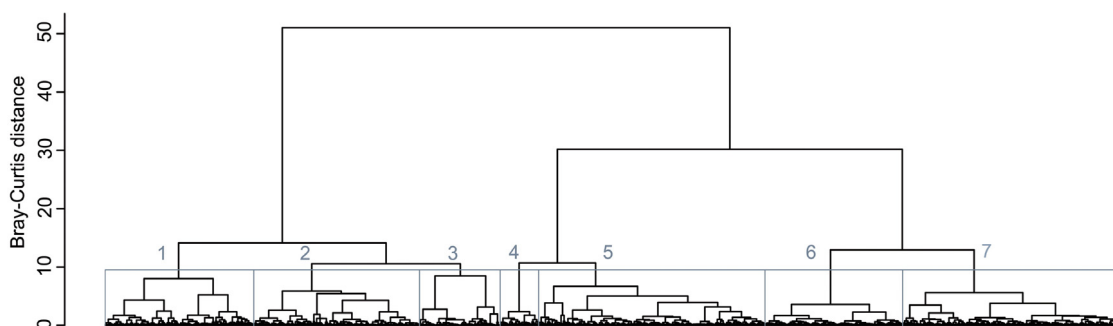


Fig. 2. Cluster dendrogram of landing per unit effort (LPUE) values for fish category per trip. The boxes highlight the cutting level selecting seven groups for exploratory analysis.

Table 2
Median, first and third quartile values for the characteristics of the trips from each group formed by hierarchical clustering method (cluster); the result of the Kruskal–Wallis test and the result of the method of analysis of indicator species (IndVal). K = test statistic.

Groups									K	P
		1	2	3	4	5	6	7		
Depth (m)	1st Qua	20.8	22.5	21.5	24.8	20	20	25	225.07	$P < 0.05$
	Median	24	25	25	34	22	23	27.5		
	3st Qua	27.5	28	29	44	25	26	30		
Vessel power (HP)	1st Qua	267	230	250	230	230	230	240	50.13	$P < 0.05$
	Median	291	290	290	290	255	230	280		
	3st Qua	340	340	340	340	291	291	320		
Gross tonnage (t)	1st Qua	55	55	55	50	55	55	55	24.50	$P < 0.05$
	Median	64	64	58	57	57	55	64		
	3st Qua	88	88	70	61	70	70	88		
Vessel length (m)	1st Qua	19	19	19	19.5	19	20	19	20.10	$P < 0.05$
	Median	20	20	20	20	20	20	21		
	3st Qua	22	22	21	22	21	21	22		
Latitude ($^{\circ}$ S)	1st Qua	24.2	24	24.1	23.9	24.1	24.2	24.2	$P < 0.05$	
	Median	24.7	24.5	24.5	24	24.4	24.7	24.8		
	3st Qua	25.5	25	25.2	24.8	25.5	25.3	26		
Month		jan to may	aug to nov	set to nov and feb	dec to feb and may	dec to apr	jan to may	set to dez		
Trimester		1 and 2	3 and 4	3 and 4	1 and 4	1 and 4	1 and 2	3 and 4		
Season		Sum/Aut	Win/Spr	Win/Spr	Spr/Sum	Spr/Sum	Sum/Aut	Win/Spr		
Year		2005 and 2006	2005 and 2006	2003 and 2005	2003, 2004 and 2007	2007 to 2009	2008 and 2009	2010 and 2011		
Indicator species	Squid, acoupa weakfish	Smooth weakfish	Jamaica weakfish	Whitemouth croaker, stripped weakfish	Southern king weakfish	Grey triggerfish, catfish, lookdown, green weakfish, guitarfish, shorthead drum, american harvestfish, snook, leatherjacket and barracuda	Kingcroaker, bluewing searobin, barred grunt, largehead hairtail, atlantic bigeye and sole		$P < 0.05$	

were determined according to landing composition, with a significant dissimilarity variation difference between them ($R = 0.48$; $p = 0.001$). Table 2 summarizes the description of each group according to the considered variables and the significance of the difference of these features per group. All variables showed a non-normal distribution ($p < 0.05$) and, except for the engine power of the vessels and season, the variances of the variables between the groups were heteroscedastic ($p < 0.05$).

All 23 fish categories were significant indicators of the groups formed by the cluster ($p < 0.05$) (Table 2). Most groups were composed by trips in coastal areas (20–30 m in depth). The fifth group clustered the shallowest trips (20 to 25 m) and presented a high abundance of southern king weakfish (*Macrodon atricauda*). The fourth group comprised trips with fishing operations ranging from 25 to 44 m in depth, covering therefore deepest places. This group of trips presented the highest landings of whitemouth

croaker (*Micropogonias furnieri*) and stripped weakfish (*Cynoscion guatucupa*).

Trips from the fifth and sixth groups were performed, mostly, by vessels with lower engine power (medians of 230 and 255 HP, respectively) than the others (medians of 290 HP), however 50% of the trips were carried out vessels of similar power in all groups. In relation to gross tonnage, trips carried out by smaller vessels composed the fourth group, presenting low inter-group variation. In the third and fifth groups, the vessels displayed lower lengths, but again, with little variation.

Group four included trips in the northernmost portion of the study area (median $24^{\circ} 48' S$), while group seven comprised the most southern trips (median $26^{\circ} S$). The fourth and fifth groups corresponded, mainly, to spring and summer trips, while the first and the sixth groups corresponded to summer and fall trips. Winter and spring trips appear more frequently in groups two, three and

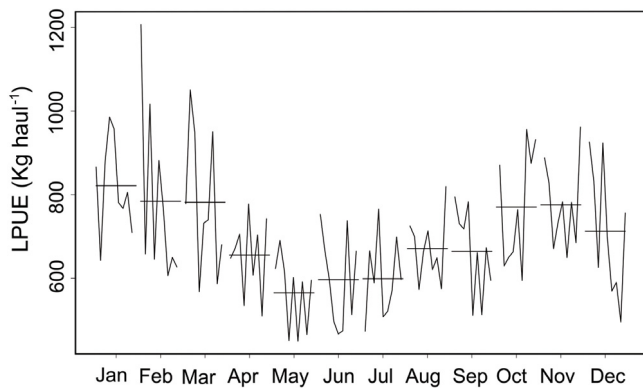


Fig. 3. Monthly variation of landings per unit effort (LPUE) values (kg trawl^{-1}) for the pair trawlers fleet, with the annual variation and average per month from 2003 to 2011. The horizontal lines and jagged lines respectively represent the average per month and annual variation.

seven. In contrast to the other groups, group seven comprised most of the trips after 2009, featuring two distinct fish compositions over the years.

3.2. Seasonal patterns

The highest total catch rates of the pair trawl fishing fleet were observed during the spring and summer months (Fig. 3). For the seasonality analysis, only the indicator categories with the highest abundance per group were selected, namely catfish, kingcroaker, bluewing searobin, whitemouth croaker, largehead hairtail, Jamaica weakfish, acoupa weakfish, smooth weakfish, southern king weakfish, grey triggerfish and barred grunt.

Of these species, the largehead hairtail category showed the strongest autocorrelation, with an annual pattern. Whitemouth croaker displayed a significant positive autocorrelation with an annual cycle and high constancy. Catfish, southern king weakfish, grey triggerfish and barred grunt displayed low significance correlations, also presenting an annual cycle, with high variability from

year to year. King croaker and Jamaica weakfish showed an annual pattern with more discrete peaks. However, bluewing searobin, acoupa weakfish and smooth weakfish did not exhibit any defined seasonal pattern, i.e. catches cannot be forecast for subsequent years (Fig. 4).

The environmental variables mean, minimum and maximum SST, and minimum chlorophyll concentrations displayed the strongest autocorrelation, with annual cycles. Mean SST and minimum chlorophyll concentrations were cross-correlated to the LPUE values from different fish categories. The MEI exhibited no defined cycle for the period, while the AAO presented a two-year cycle for the analyzed period (Fig. 5). SST presented highest values in February and lower values in July and August, while chlorophyll concentrations exhibited lower values in January and higher values in August (Fig. 6).

3.3. LPUE and environmental variables

Chlorophyll concentrations displayed a high inverse correlation with SST with a lag of one month. AAO correlated significantly only with MEI presenting a two-month lag, without seasonality. The MEI correlated presenting a four-month lag with chlorophyll concentrations and presenting a three-month lag with SST, also without displaying any seasonality (Fig. 7). Even though SST and chlorophyll concentrations presented a strong collinearity, some species showed greater correlation to one or both of these variables. In addition, the time lag of the relationship of these variables with catch rates were different, which allows a more detailed analysis of their influence on landings. Thus, both parameters were maintained in the analyses.

Almost all species were significantly correlated to SST, with the exception of smooth weakfish and bluewing searobin. On the other hand, only bluewing searobin was not significantly correlated to with chlorophyll concentrations. Catfish, largehead hairtail and southern king weakfish were correlated with AAO, but with no clear seasonality, while whitemouth croaker, grey triggerfish and southern king weakfish displayed no significant correlation with MEI (Table 3). Fig. 8 depicts the correlations between the LPUE of the categories and environmental variables with the strongest

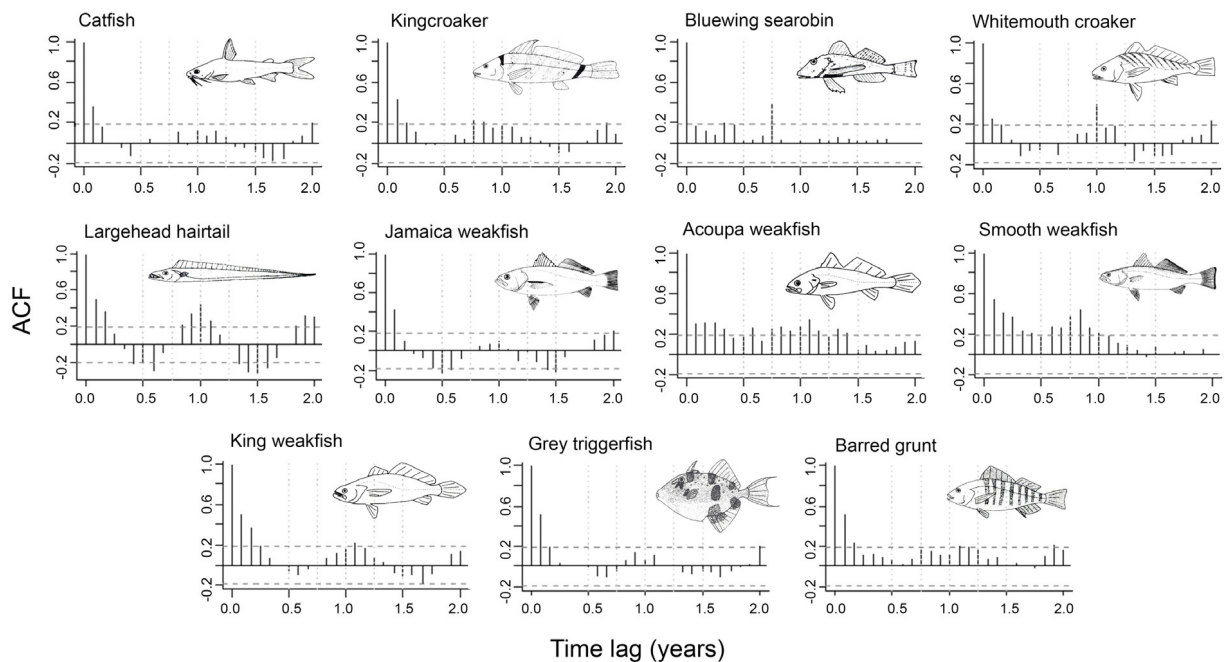


Fig. 4. Autocorrelation functions (ACF) with two years' time lag of the indicator species of the groups formed by the cluster. The horizontal dotted lines represent the confidence interval of 95%. Fish drawings based on Carvalho-Filho (1999) and Cervigón et al. (1992).

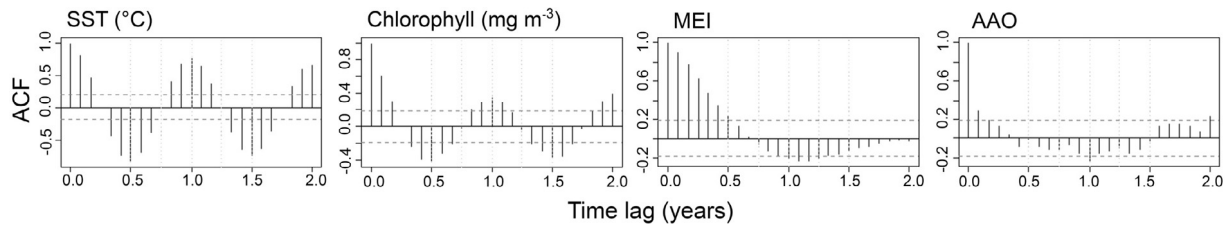


Fig. 5. Autocorrelation functions (ACF) with two years' time lag of SST (sea surface temperature — °C), chlorophyll concentration (mg m⁻³), MEI (Multivariate El Niño Index) and AAO (Antarctic Oscillation Index). The horizontal lines represent the confidence interval of 95%.

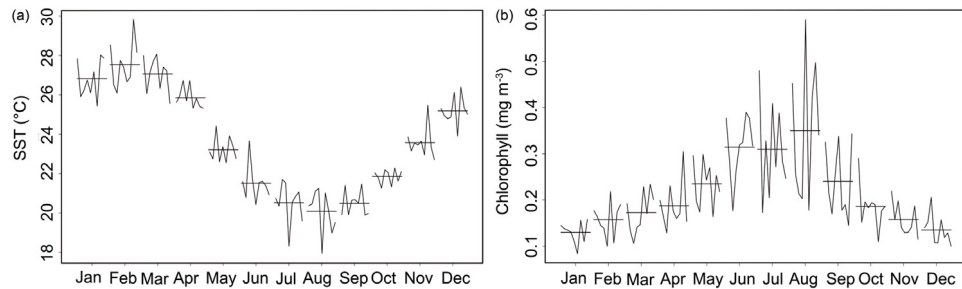


Fig. 6. Monthly variation of SST (sea surface temperature — °C) (A) and chlorophyll concentration (mg m⁻³) (B) in the study area. The horizontal lines and jagged lines respectively represent the monthly average and annual variation from 2003 to 2011.

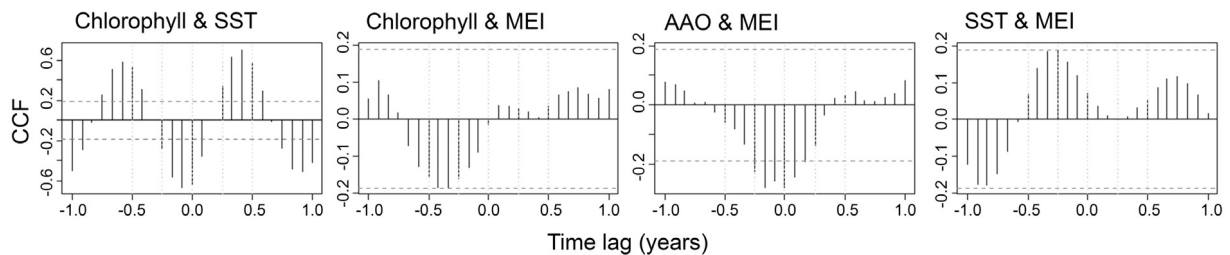


Fig. 7. Cross correlation functions (CCF) between SST (sea surface temperature — °C), chlorophyll concentration (mg m⁻³), MEI (Multivariate El Niño Index), and AAO (Antarctic Oscillation Index). The horizontal dotted lines represent the confidence interval of 95%.

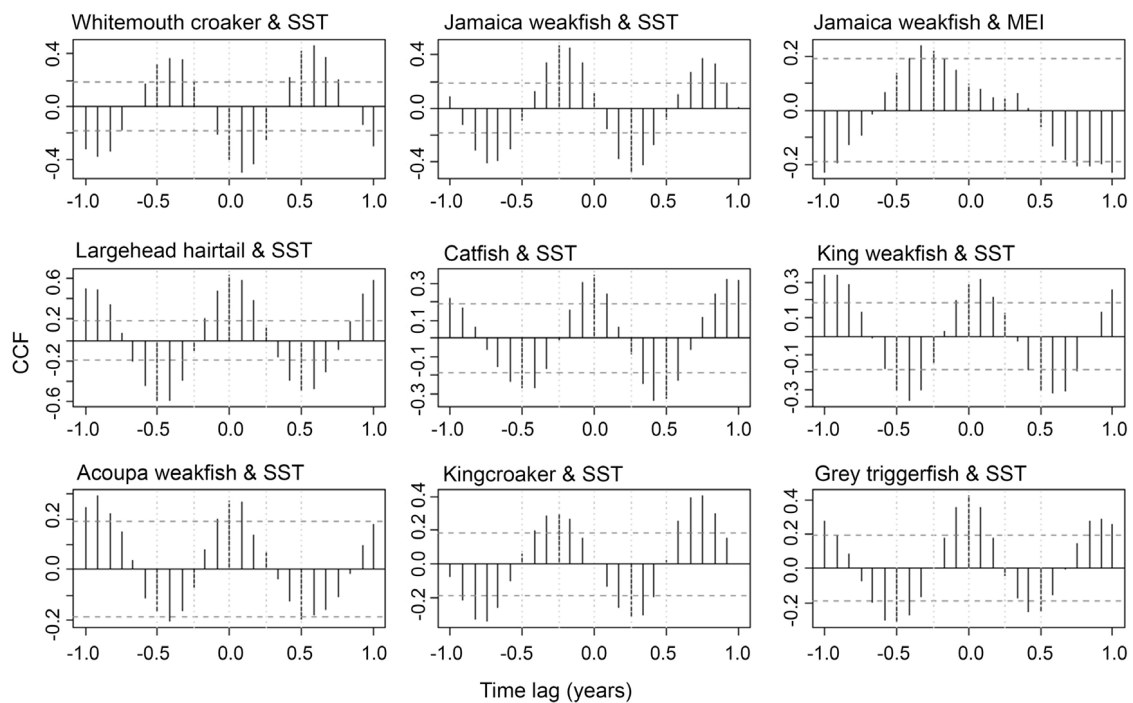


Fig. 8. Strongest cross correlation functions (CCF) with two years' time lag between environmental variables and LPUE (Landings per unit effort) of different categories of fish. SST = sea surface temperature (°C); MEI = Multivariate El Niño Index. The horizontal dotted lines represent the confidence interval of 95%.

Table 3

Maximum correlation values and their lag in months of landings per unit effort (LPUE – kg haul⁻¹) time series for each category in relation to environmental variables. CCF = Cross correlation function; SST = Sea surface temperature; SCC = Sea chlorophyll concentration; AAO = Antarctic Oscillation Index; MEI = Multivariate El Niño Index.

	Mean SST		Min SCC		AAO		MEI	
	CCF	Time lag	CCF	Time lag	CCF	Time lag	CCF	Time lag
Whitemouth croaker	–0,50 [*]	1	0,56 [*]	2	–0,14	1	–0,16	–2
Jamaica weakfish	–0,49 [*]	3	–0,47 [*]	–1	0,12	10	0,24 [*]	–4
Kingcroaker	0,41 [*]	9	0,39 [*]	4	–0,19	–6	0,23 [*]	4
Catfish	0,35 [*]	0	0,33 [*]	–5	–0,31 [*]	–3	–0,24 [*]	2
Bluewing searobin	–0,11	2	0,10	–11	0,19	–2	–0,20 [*]	9
Largehead hairtail	0,64 [*]	0	0,52 [*]	–5	–0,28 [*]	–7	0,23 [*]	–5
Grey triggerfish	0,43 [*]	0	0,42 [*]	–5	–0,18	2	0,14	8
Southern king weakfish	–0,37 [*]	–5	0,40 [*]	–5	–0,33 [*]	–4	0,12	–12
Acoupa weakfish	0,30 [*]	–11	–0,24 [*]	–5	–0,19	–10	0,32 [*]	–7
Smooth weakfish	0,19	–12	–0,20 [*]	1	–0,18	1	0,26 [*]	–5

^{*} Significant correlation.

seasonality. Jamaica weakfish was the only category that displayed seasonality with MEI.

The LPUE values for catfish, largehead hairtail and grey triggerfish displayed a direct correlation with SST with no time lag, i.e., during the same month a peak of high temperature was observed, an increased LPUE for these species was also detected. Whitemouth croaker and southern king weakfish displayed correlations with SST with a time lag of one month. However, the former exhibited an inverse relationship, and the latter, a direct relationship. Acoupa weakfish exhibited a direct correlation presenting a one month lag with temperature. Jamaica weakfish and king croaker displayed a three-month lag in an inverse correlation with SST, and only Jamaica weakfish exhibited an inverse correlation with MEI with a four-month lag.

4. Discussion

Pair trawling is a fishing method that presents high fishing power with a highly multispecific catch and no specific target species, but presents some categories, in turn, that make up the bulk of its capture, mostly fish from the Sciaenidae family (Haimovici, 1998). According to the cluster analysis, fleet trips proved non-homogeneous in relation to their catch composition in the period, presenting different species abundance patterns that may be related to environmental and/or operational variables.

In the case of the main Sciaenidae fish evaluated herein, which require about 1–2 years to recruit and display a lifespan of at least 8 years (Cergole et al., 2005), the response in stock size to environmental change occurs with a long time lag. Therefore, as the present study investigated only two years of time lag, the applied analysis verified the variables that correlate with changes in the abundance of catches during this period, investigating the interference of these variables on population dynamics and/or stock catchability.

A cluster analysis also demonstrated that the physical characteristics of the vessels are heterogeneous in the fleet travels, albeit with a small variation, as most of the travel is performed by medium-sized vessels (19 to 22 m; 230–340 hp). This variation does probably not result in differences in fishing capacity and is not, therefore, an explanation for the observed differences in catch compositions.

A change in catch composition after 2009 was detected, where the cluster grouped trips performed more often in higher latitudes (24° 11'–26°S) and deeper (25–30 m), with higher frequency/abundance of kingcroaker, largehead hairtail and flounder, as well as lower frequency of catfish, grey triggerfish and weakfish. This is related to the establishment of marine protected areas on the coast of the state of São Paulo in the same year, in which pair trawling was banished from the coastal domain where this fleet

usually operated, being forced to fish at greater depths and search for more coastal fishing grounds in other states, especially to the south (Rolim and Ávila-da-Silva, 2016), resulting in the observed catch composition change.

Sea surface temperatures were lower during the winter months (20 to 21 °C) and higher during the summer months (27 to 28 °C). This corroborates the dynamics described by de Castro et al. (2006) for the Brazilian southeast continental shelf. Bottom temperature was not addressed in this study, however it is important to note that, according to these authors, the lower layer presents a different dynamic, in which lower values occur in summer (< 18 °C), and are related to penetration of the South Atlantic Central Water (SACW) in the region during this time of year, conferring distinct horizontal and vertical gradients. This water mass brings nutrients, attracting shoals and, therefore, explains the higher yields of the pair trawling fleet during the spring/summer.

Chlorophyll concentrations and sea surface temperature were highly correlated, since increases in primary productivity are related to the upwelling of cold, nutrient-rich waters (de Castro et al., 2006). The results of this study corroborate this statement, indicating a strong inverse correlation of these variables with an annual cycle, where sea surface temperatures in the summer are high and chlorophyll concentrations are low, while the opposite is observed in winter.

Although SACW reaches the inner shelf region in summer (de Castro et al., 2006), the chlorophyll concentrations in the present study were found to be higher in the winter. This is due to the fact that, besides the SACW not presenting a strong upwelling in the area (de Castro et al., 2006), a shift of the confluence between the Brazil Current and the Malvinas Current (Subtropical Convergence) to the north occurs during this time of year (Zavialov et al., 1998). This shift carries cold surface water mass rich in nutrients (Brandini et al., 2000) and of low salinity originating in sub-Antarctic waters of the Malvinas current and stemmed waters of the estuarine complex of the Patos Lagoon–Mirim Lagoon in south Brazil and the Plata River in south Uruguay (Zavialov et al., 1998). This movement is driven north by winter cold fronts and by the pressure gradient of the estuarine complex (Soares, 2003), which reduces the sea surface temperature and increases the primary production in the region.

Seasonal LPUE fluctuations are often documented in the literature, and many have been linked to the fishery's environmental and operational variables (Bigelow et al., 1999; Damalas et al., 2007; Dawe et al., 2007; Hobday and Tegner, 2002). In the present study, the environmental variables presenting the strongest correlations with species catch were sea surface temperature and chlorophyll concentrations. Indeed, most advanced life stages, such as juveniles and adults, exhibit the potential to respond to changes in the environment, and can also display an active preference

for certain temperature ranges (Clark and Green, 1991; Coutant, 1977). Moreover, high chlorophyll concentrations may act as shoal agglomeration forces, by providing food sources, either directly, in which planktophagous fish are attracted, and indirectly, attracting predatory fish that feed on them (Mann, 1993).

The understanding of the relationship between stock distribution and environmental variables is essential, since this information enables the development of a habitat map, which provides an ecosystem description in both space and time, and assists with fisheries and stock management (Stuart et al., 2011). Most of the fish targeted by the pair trawlers landings evaluated in the present study displayed a high correlation to environmental variables. These agglomerations in the fishing areas during specific conditions by each species may be related to reproductive and migration patterns in the region, which will be discussed herein for the main landed fish categories.

The whitemouth croaker is, by volume, the most landed demersal species in Southern Brazil (Cergole et al., 2005). These organisms display a wide geographical distribution and have been recorded throughout a wide a temperature range (11 to 31.6 °C) (Isaac, 1988). However, in this study, species yield was inversely correlated with temperature, where increased landings were observed after a month of low surface temperature and after two months of high chlorophyll concentrations. Therefore, this movement follows the winter cold water, rich in nutrients.

Indeed, according to Vazzoler and dos Santos (1965), this species moves in schools presenting a migration pattern in which, during the summer, agglomeration are found further south (33°S), while during winter the species moves northwards (28°S), following the displacement of the subtropical convergence (Vazzoler, 1963), seeking warmer waters north. Although the stocks from southeast Brazil (between 23 and 29°S) do not present a seasonal migration pattern (Vazzoler, 1965, 1963), it is likely that stock migration from the south (between 29 and 33°S) influences the catches in the study area (between 23° 56'S and 27° 43'S). Hare and Able (2007) also described a strong relationship between croaker (*Micropogonias undulatus*) catches and sea temperature for the North Atlantic Ocean, for both adults and juveniles, relating higher catches in warmer waters.

The whitemouth croaker in the region is a partial spawner, and reproduction occurs throughout the year (Vazzoler et al., 1999). Individuals from the southeastern stock form aggregations that move from the coast to open sea, where they spawn (Vazzoler, 1971), and favorable local lagoons and estuarine regions are used by juveniles for food and growth (Menezes and Figueiredo, 1980). In addition, Carneiro et al. (2005) highlighted a spawning activity peak during winter (August), which also explains the aggregation observed in the fishery area.

However, LPUE values for catfish, acoupa weakfish and southern king weakfish followed the higher spring–summer surface temperatures. Even with the penetration of cold water from the SACW during those months of the year, this event occurs in the subsurface and does not often reach the coastal region over 25 m in depth, mainly in the central area, that displays an extensive continental shelf (de Castro et al., 2006). Therefore, these demersal species that exhibit a more restricted distribution near the coast (around 20 m deep) (Menezes and Figueiredo, 1980) are probably attracted to warmer spring–summer coastal waters.

This time of year is also when southern king weakfish breeding and recruitment occurs (Cergole et al., 2005), and when acoupa weakfish spawning peaks (Almeida, 2008). Both species, as well as the Ariidae (catfish) family occupy estuarine waters while young and move to adjacent shelf waters to reproduce (Chao et al., 2010; Lowe-McConnell, 1999; Vazzoler, 1991). The study area presents many estuaries, with three noteworthy areas, due to their influence in the region: the Santos estuary, Cananéia-Iguape lagoon system and Paranaguá estuary (Rossi-Wongtschowski and Madureira,

2006). As indicated by Lowe-McConnell (1999), a higher abundance of fish in estuaries is observed during the warm season in the Brazilian southeastern coast. This period of the year also presents high river discharges, due to high pluviosity indices, leading to high plankton concentrations (Lowe-McConnell, 1999), therefore explaining the high catches of these fish categories detected by the present study during that time of the year.

The largehead hairtail also showed high landings values, related to high surface temperatures periods, however, unlike the above mentioned species, this species has demerso-pelagic habits with a wide geographical distribution (up to 300 m isobaths). Thus, it a preference for warm water is not evident, since the species comes into contact with the cold and nutrient-rich SACW, coinciding with one of the breeding peaks and recruitment of the species (Bellini, 1980; Cergole et al., 2005).

Jamaica weakfish showed an LPUE peak of three months after low temperature values, and four months after the highest chlorophyll concentration values, with two annual capture peaks (November and February). During this period, both environmental variables occur intermediate values, and other studies have reported that the species follows relatively warm waters (de Figueiredo, 1981), probably related to its spawning season (November to March) (Cergole et al., 2005).

Castro et al. (2005) noted that grey triggerfish catches were enhanced during autumn and winter, coinciding with a drop in higher value species catches. This was not observed in the present study, since this species exhibited a positive correlation with temperature, with most captured occurring during summer and fall, when the capture of sea whitemouth croaker and southern king weakfish, for example, are also high, both important species for the fleet. The high LPUE during summer coincides with the reproduction of the species (Bernardes and Dias, 2000), in which individuals group in shoals to spawn in the region (Castro et al., 2005).

Several studies have linked fish life history to the Northern Hemisphere Annular Mode (Arctic Oscillation), which in turn, has been correlated to temperature (Dippner and Ottersen, 2001; Hare and Able, 2007). In the present study, the AAO showed a correlation only with the MEI, in which inverse peaks were related without seasonality. Although El Niño events are related to temperature increases in the South Atlantic (Enfield and Mayer, 1997), in the present study, the MEI presented a peak three months after the high temperature peak and four months after the lowest chlorophyll concentration values; therefore, climate indices did not apparently influence these variables during a two-year time lag in the study area.

As marine organisms are sensitive to environmental variations, changes in climate dynamics have the potential to influence populations, both directly and indirectly. The prediction of ocean changes for the following decades suggested by IPCC (2007) encompasses sea-level rises, ocean acidification, increases in sea surface temperatures, intensification of cyclones and changes in precipitation regimes and run-offs. The consequences of these changes may display both regional and worldwide consequences, altering fish population dynamics and fishing activities. The results presented herein indicate a significant relationship between environmental conditions and fishery landings, which has been discussed as also correlated to fish dynamics, especially to reproduction and migration patterns. In face of a climate change scenario, if the stock already presents an overfishing status, the situation is intensified by increasing the susceptibility and decreasing the recovery capacity of the population. To mitigate this, effective management measures for stock preservation are important, which require continuous fisheries monitoring as well as larvae and juvenile samplings in order to better understand the life cycles of exploited species.

Therefore, landings of the pair trawl fishing fleet evaluated herein can be concluded as displaying seasonal patterns, with higher yields during spring and summer. The main influences on catches were sea surface temperature and chlorophyll concentrations, probably related to fish distribution patterns and reproductive activity. In this context, it is crucial to continue to monitor fisheries, as well as generate more specific knowledge related to the role that environmental conditions play in fish biology. This is important to assess the impacts that changes in oceans dynamics may cause to fish populations in the long run, enabling to forecast future conditions, as well as the design of a management plan that might circumvent this issue.

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